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# IMPACT OF NON-HOOKEAN BEHAVIOUR ON MECHANICAL PERFORMANCE OF HYBRID COMPOSITES

Christen Malte Markussen<sup>1</sup>, Bo Madsen<sup>1</sup>, Hans Lilholt<sup>1</sup> and Tom Løgstrup Andersen<sup>1</sup>

<sup>1</sup> Section of Composites and Materials Mechanics,  
Department of Wind Energy, Technical University of Denmark  
P.O. Box 49, Frederiksborgvej 399, DK-4000 Roskilde, Denmark  
Email: [cmar@dtu.dk](mailto:cmar@dtu.dk), web page: <http://www.vindenergi.dtu.dk>

**Keywords:** Carbon fibres, Glass fibres, Hybrid composites, Stress strain curves, Modelling

## ABSTRACT

Hybrid composites, based on unidirectional fibres of carbon and glass, in an epoxy matrix have been used to investigate the possibility of a hybrid effect. The hybrid effect is observed experimentally by values for both composite strength and composite failure strain, which are increased compared to a simple model. The introduction of an increase of the failure strain of the carbon fibre part (the “fibre”) of the composite, described by a factor  $H$  for the increase of the failure strain, results in theoretical curves for strength and failure strain, which are in general agreement with the experimental data. For the present hybrid composites a value of  $H = 1.22$  is required, meaning a positive hybrid effect on “fibre” strain of 22%. It is thus concluded that the simple concept of a hybrid factor  $H$  for the fibre failure strain can describe the observed hybrid effect satisfactorily.

## 1 INTRODUCTION

A growing niche in the wind energy market is the multi-MW class turbine used primarily for off-shore sites [1]. The growing interest in off-shore turbine placement is a result of the shortage of attractive on-shore sites [2]. Due to the extraordinary costs connected to off-shore construction (foundation, tower, grid connection), there is a larger incentive to increase the power production from the individual turbines. Higher output turbines warrant greater rotor diameters, which in turn warrant stiffer and stronger blades to maintain tower clearance requirements, while keeping the overall mass to a minimum. To increase the bending stiffness of the blade the obvious design route is to add material to the main laminates in the blade. This is however inherently coupled to an increase in blade mass, putting further stress on the structure. Alternatively a material with lower density and higher stiffness can be employed. The most apparent choice would be carbon fibres; however moving fully from glass fibre to carbon fibre entails a significant increase in the cost of the blade.

Combining a stiff Low Elongation Component (LEC) with a strong High Elongation Component to obtain a “hybrid” composite with intermediate stiffness properties appears attractive. Early experimental work [3, 4, 5, 6, and 7] proved that such a hybrid does indeed perform closely to Rule of Mixture (RoM) with respect to elastic properties. However due to complicated failure mechanics, ultimate strength measurements proved unpredictable and with great scatter. Dependency on composite architecture [6, 5, and 7] as well as testing methodology [5, 7] was shown to influence results. Added to this, many experiments also demonstrated that first failure occurs at roughly the failure strain of the LEC, reducing the strength below both the individual constituent materials. This apparently intrinsic characteristic, limited the usefulness of this type of material, and research was to a large extent arrested. With the maturing wind energy sector progressively demanding stronger and stiffer materials, interest in hybrids has been renewed.

This study investigates hybrid composites made from modern UD carbon and glass fibres using vacuum infusion to best represent the manufacturing technology of the wind turbine industry.

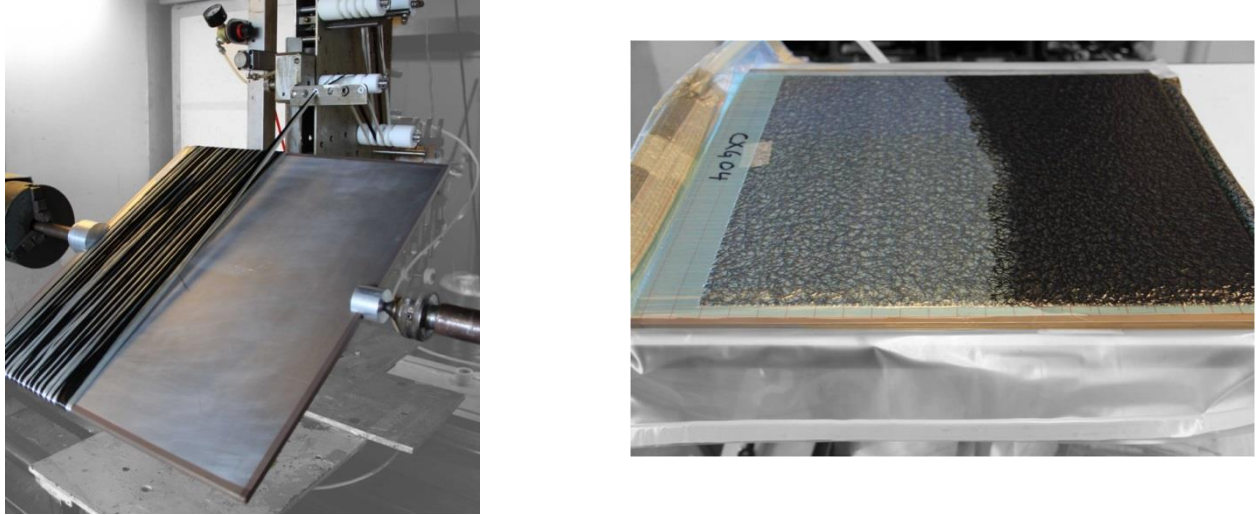


Figure 1: Filament winding and vacuum infusion of hybrid composites

## 2 METHODS AND MATERIALS

For this study, materials selected were all commercially available carbon fibre, glass fibre and epoxy. As glass fibre benchmark the higher modulus PPG Hybon Innofiber with a 2026 size was chosen, since it is rapidly becoming the industry choice for load carrying laminates. For carbon the inexpensive Zoltek Panex35 50k was chosen since it is the obvious choice for low cost composite structures, like wind turbine blades. The resin system chosen was Dow Airstone epoxy due to its representative processing and mechanical properties.

### 2.1 Manufacturing

Due to the high cost and effort involved in having an experimental hybrid-fabric developed and manufactured, laminate specimens were filament wound. Furthermore filament winding ensures high alignment and eliminates backing fibres and stitching yarn and the potential effects introduced by these elements (see Fig. 1 (left)). To achieve good and representative material quality, manufacturing of laminates was realized using the Vacuum Infusion Process (VIP) (see Fig.1 (right)). The laminates were cured for 5h@50C and post cured for 2h@90C. Overall this process enables low porosity levels, high fibre volume fraction and consistent material quality.

Laminates with hybridization ranging from neat carbon/epoxy to neat glass/epoxy specimens were manufactured with three intermediate levels. Glass fibre roving and carbon tows were wound unto an aluminium tool plate pre-treated with a release agent. For the hybrid laminates the three intermediates were realized with all rovings being applied simultaneously to the tool plate (as seen in Fig. 1 (left)).

Exp data, C + G, Risø								
code	Vfca	Vfgl	Vcca	Vcgl	Ec exp	Scu	ecu	E=Scu/ecu
Glass/epoxy	0.000	0.587	0.000	1.000	47.4	1023	0.0237	43.16
Low level hybrid	0.152	0.415	0.304	0.703	64.7	1007	0.0153	65.82
Medium hybrid	0.205	0.378	0.366	0.641	71.7	966	0.0131	73.74
High level hybrid	0.308	0.275	0.550	0.444	85.0	1212	0.0137	88.47
Carbon/epoxy	0.529	0.000	1.000	0.000	110.2	1337	0.0119	112.35

Table 1: Experimental data for volumetric composition and mechanical properties.

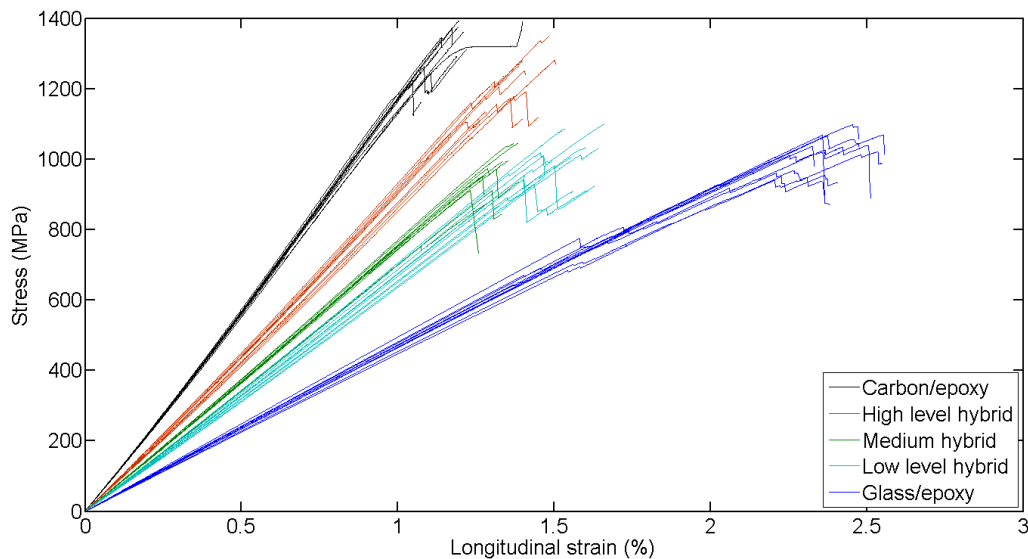


Figure 2. Hybrid composites, stress-strain curves for all individual tests in tension.

This configuration is chosen to resemble a fabric where carbon tows are placed discretely with consistent spacing in between glass rovings, designated “in-ply” architecture. By applying several glass rovings and the carbon tow simultaneously the highest degree of randomization is achieved, and thereby homogenizing the material as much as possible.

## 2.2 Testing

All specimens have bi-directional glass-fibre/epoxy tabs mounted and are cut using a water cooled diamond blade. A total of 10 specimens were tested in each series to ensure good statistical background. Testing was conducted using an Instron servo-hydraulic test machine (Instron, High Wycombe, UK) with a cross-head speed of 1mm/min. Strain gauge extensometers were mounted on both sides of the specimens to compensate for non-aligned specimens.

## 3 RESULTS

The results for the five hybrid composites are plotted in Fig. 2. For each hybrid composite all 10 individual stress-strain curves in tension are shown in Fig. 2. It is clear that all curves demonstrate various degrees of curvature, an *upwards* curvature for all hybrid composites with a content of carbon fibres, while a *downwards* curvature is seen for the glass fibre composite. This curvature is analysed by plotting the tangent modulus (the local stiffness parameter  $E$ ), versus strain, as shown in Fig. 3 for the pure carbon fibre (hybrid) composite and for the pure glass fibre (hybrid) composite.

It is clear the carbon composite demonstrates a tangent modulus, which *increases* (nearly) linearly with strain, while the glass composite demonstrates a tangent modulus, which *decreases* (nearly) linearly with strain. This observation implies that the relation between stress and strain is a second order relation, with a positive curvature for carbon composites and a negative curvature for glass composites. This result is used in the analysis and modelling described in section 4.

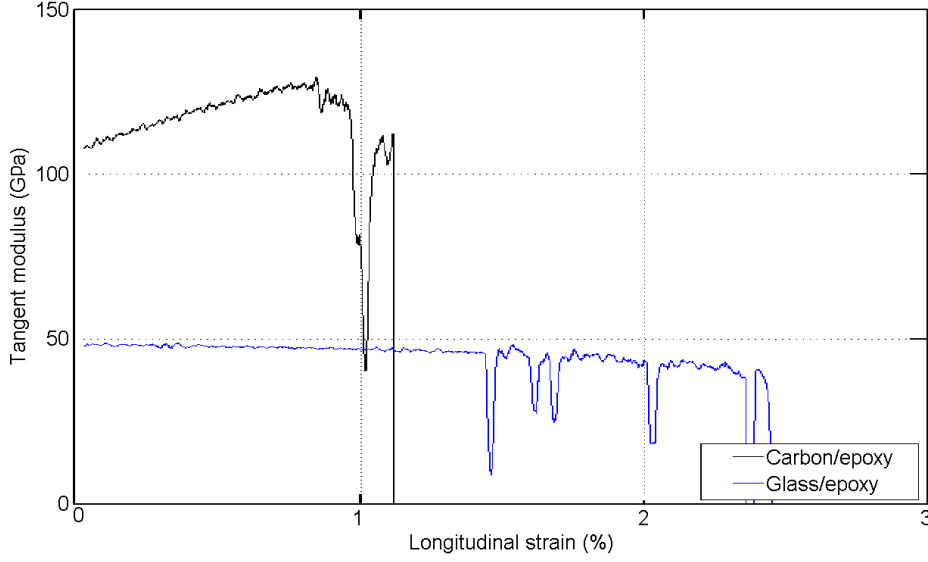


Figure 3. Composite with only carbon fibres (black curve), and composite with only glass fibres (blue curves), tangent modulus versus strain in tension.

#### 4 MODELLING

The results will be analysed and modelled on the basis of the concept of “brittle fibres” in a more “ductile matrix”. In the present hybrid composites the carbon fibre part constitutes the “brittle fibres”, and the glass fibre part constitutes the “ductile matrix”. The fibre volume fraction  $V_f$  of conventional fibre / matrix composites is equivalent to the carbon fibre fraction  $V_{c,ca}$  of the hybrid composite. The original (simple) model for composites with (long unidirectional) brittle fibres in a ductile matrix was proposed by Kelly and Tyson [8]. They used the failure strain  $\epsilon_{fu}$  of the fibres as a controlling parameter for the strength of composites at fibre volume fractions varying from 0 to 1. At high volume fractions of fibres the failure of the composite occurred when the fibres failed at  $\epsilon_{fu}$ , this *strain criterion* was used to calculate the composite strength from the rules of mixtures, with the matrix contribution equal to the stress of the matrix at the strain  $\epsilon_{fu}$ :

$$S_{cu} = V_f \cdot S_{fu} + V_m \cdot S_m(\epsilon_{fu}) \quad (1)$$

At low volume fractions of fibres, the failure of (the rather few) fibres at  $\epsilon_{fu}$ , allows the matrix to carry the load lost from the fibres, such that the composite can take further load until the matrix reaches its failure strength  $S_{mu}$ . This *stress criterion* relates to the matrix part, i.e. fraction  $V_m$  of the composite, and the composite strength becomes:

$$S_{cu} = V_m \cdot S_{mu} \quad (2)$$

In a diagram of composite strength vs  $V_f$  these two equations are two straight lines with an intersection at  $V_{f(thresh)}$ , called the minimum volume fraction or the threshold volume fraction. In their model Kelly and Tyson [8] focus only on the strength of the composites, they do not consider in detail the stress-strain curves of the composites, and they do not evaluate the failure strains of the composites in general, although they imply a failure strain of  $\epsilon_{fu}$  for the composites at  $V_f$  larger than  $V_{f(thresh)}$ . The composites at low  $V_f$  show fibre failures without failure of the composite, this is called multiple fibre fracture. The concept of load transfer between fibre and matrix allowed Kelly and Tyson to introduce a simple model with constant interfacial shear stress, leading to the concept of a

critical fibre length, which is loaded to its failure strength at its midpoint. The relation between the relevant parameters is:

$$\frac{l_c}{d} = \frac{S_{fu}}{2\tau} \quad (3)$$

This means that for low  $V_f$  composites at strain equal to  $\epsilon_{fu}$ , the fibres will fail into short segments, of lengths between  $\frac{1}{2} l_c$  and  $l_c$ . The average length of these short fibres will be:

$$l_{av} = 1.364 \cdot (\frac{1}{2} l_c) \quad (4)$$

where the factor 1.364 is noted by [9].

The original unidirectional long fibre composite at low  $V_f$ , will at strains beyond  $\epsilon_{fu}$  become a composite with short aligned fibres of average length  $l_{av}$ . These short fibres give a stress contribution  $S_{f,av}$  to the composite, such that the composite stress at any strain beyond  $\epsilon_{fu}$  is:

$$S_c(\epsilon_c) = V_f \cdot S_{f,av} + V_m \cdot S_m(\epsilon_c) \quad (5)$$

The *stress criterion* for the low  $V_f$  composite is that the matrix reaches its failure strength  $S_{mu}$ :

$$S_{cu} = V_f \cdot S_{f,av} + V_m \cdot S_{mu} \quad (6)$$

The corresponding failure strain  $\epsilon_{cu}$  of the composite is the value of  $\epsilon_c$  when  $S_c(\epsilon_c) = S_{cu}$ . The equations (1) and (6) allow the composite strength vs  $V_f$  diagram to be established for the case including the short fibre stress contribution.

The stress-strain curves for the composites can be calculated, if the stress-strain relations are known for the fibres and for the matrix. Normally the fibres are assumed to show linear elastic behaviour with a constant stiffness ( $E_f$ ), while the stress-strain relation for the matrix is often not specified or discussed. In the present study the carbon fibres and their composites show stress-strain curves with an increasing stiffness  $E_f$  with increasing strain. The analysis above in section 3 shows a good linear relation between  $E_f(\epsilon_f)$  and strain  $\epsilon_f$ , this implies that the relation between stress and strain is a second order relation:

$$S_f = E_{f0} \cdot \epsilon_f + \frac{1}{2} A_f \cdot (\epsilon_f)^2 \quad (7)$$

In order to model the complete stress-strain curve for composites, it is also assumed that a second order relation can be used for the matrix:

$$S_m = E_{m0} \cdot \epsilon_m + \frac{1}{2} A_m \cdot (\epsilon_m)^2 \quad (8)$$

This relation is a good description for polymers, and for the glass composite part of the hybrid composites. It should be noted that the carbon fibre and corresponding composites have *positive*  $A_f$ , while the matrix have *negative*  $A_m$ . The composites all have unidirectional fibres (long or short) and thus the strains are equal

$$\epsilon_c = \epsilon_f = \epsilon_m \quad (9)$$

On the basis of the above equations (1), (6), (7), (8) and (9), it is possible to calculate the stress-strain curves for composites for varying  $V_f$ , the composite strength vs  $V_f$ , and the composite failure strain vs  $V_f$ . These three relations are conveniently plotted in diagrams. The experimental data for strength and failure strain of the hybrid composites are plotted in these diagrams, as shown in Fig. 4, 5 and 6. It is clear that the experimental values are over and above the theoretical curves of the simple

theory. This was earlier (1970's) seen as a hybrid effect in composites with two types of fibres, normally carbon and glass, implying that the low strain fibres were in some way supported by the high strain fibres, leading to an extra stress contribution over and above the simple rules of mixtures values.

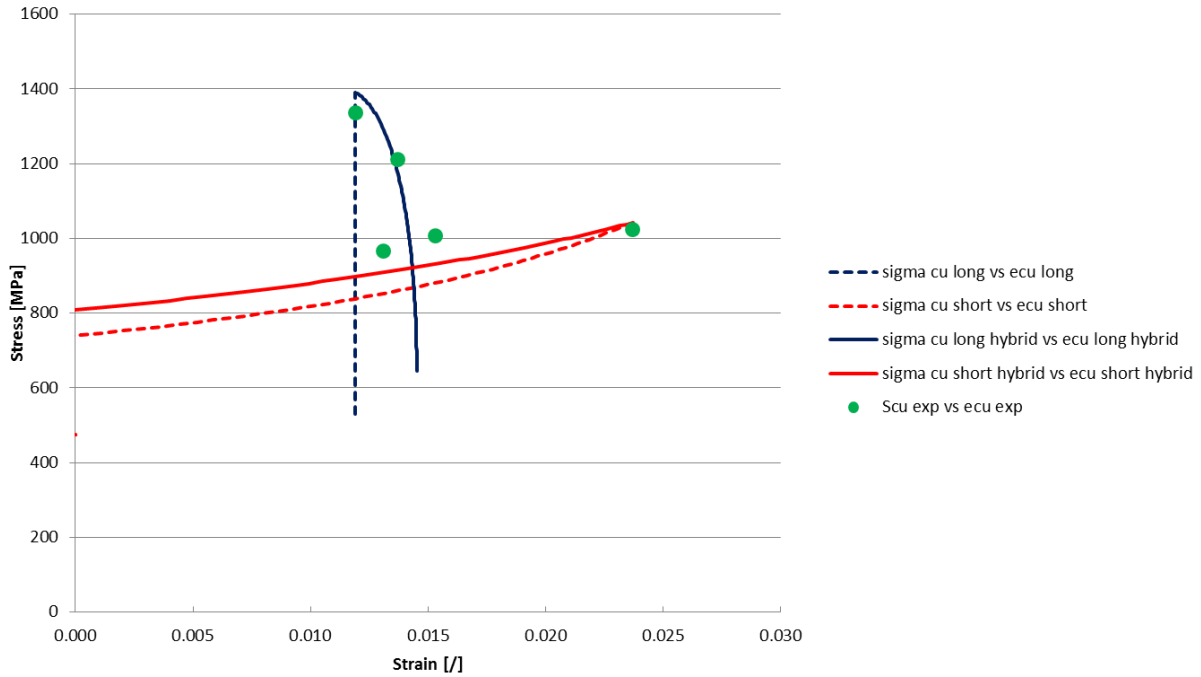


Figure 4. Hybrid composites, composite strength vs composite failure strain. Green points are the 5 experimental points. Red and blue dotted curves are simple theory eqs. (1) and (6), fully drawn red and blue curves are theory including hybrid effect with  $H = 1.22$  eq (10).

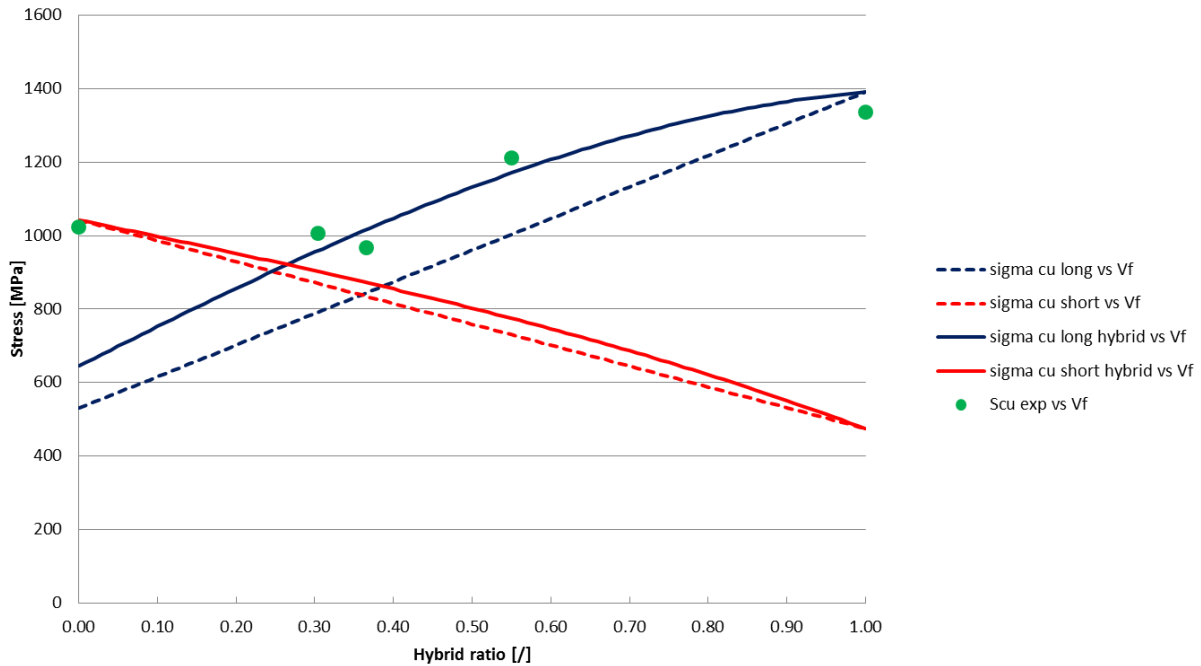


Figure 5. Hybrid composites, composite strength vs  $V_{c,ca} = V_f$ . Green points are the 5 experimental points. Red and blue dotted curves are simple theory eqs. (1) and (6), fully drawn red and blue curves are theory including hybrid effect with  $H = 1.22$  eq (10).

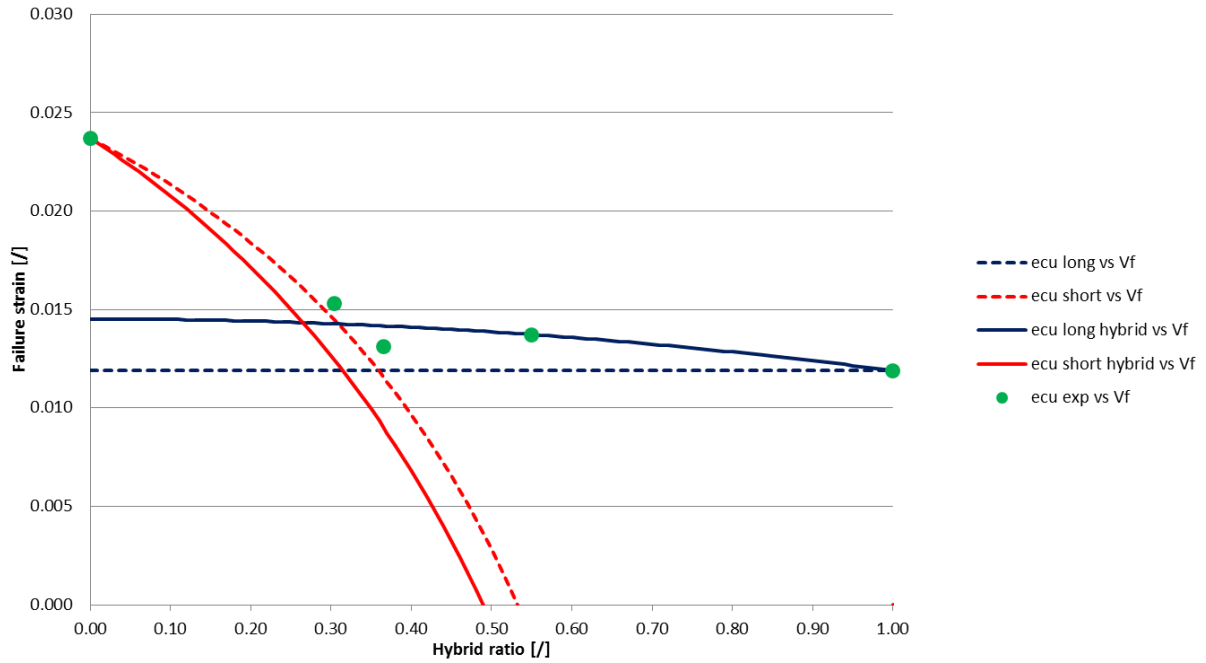


Figure 6. Hybrid composites, composite failure strain vs  $V_{c,ca} = V_f$ . Green points are the 5 experimental points. Red and blue dotted curves are simple theory eqs. (1) and (6), fully drawn red and blue curves are theory including hybrid effect with  $H = 1.22$  eq (10)

For metal matrix composites, with ductile fibres in a (more) ductile matrix, Mileiko [10] used an analytical power law for the stress-strain relation for both fibres and matrix, to calculate the composite stress-strain curves. Mileiko [10] showed that the ultimate tensile strength of the composite implied that the (low strain) fibres were able to be strained beyond their normal ultimate strain. Mileiko presented the stress strain curves, the strength vs.  $V_f$ , and the failure strain vs.  $V_f$  diagrams, with experimental data for three different metal matrix composites, and established good agreement.

Inspired by the possibility that the low strain fibre can strain beyond its normal failure strain, it is proposed to *empirically* introduce this possibility for the hybrid composites, and allow the carbon fibre part to reach larger strains than the normal (experimentally determined) failure strain,  $\epsilon_{fu}$ . It is suggested that the hybrid effect on the fibre failure strain is strongest when the amount ( $V_{c,ca}$ ) of the carbon fibre part is low (and the amount of the surrounding glass fibre part is high), and that the effect dies away at increasing  $V_{c,ca}$  (equivalent to  $V_f$ ), following a parabolic relation:

$$\epsilon_{fu} = [(1 - H) \cdot V_f^2 + H] \cdot \epsilon_{fu,0} \quad (10)$$

The parameter  $H$  is the factor on  $\epsilon_{fu,0}$ , giving the maximum effect on  $\epsilon_{fu}$ , such that  $\epsilon_{fu(max)} = H \cdot \epsilon_{fu,0}$ , which in this case occurs at  $V_{c,ca} = V_f = 0$ . This relation is shown in Fig. 7 for the values of the carbon fibre part in the present hybrid composites.

An empirical value of  $H = 1.22$  is used in Fig. 4, 5 and 6, to obtain general agreement with the (five) experimental data points. In Fig 4 only the tensile strength and the failure strain are shown, while the (individual) stress strain curves are omitted, so that the curves in Fig 4 represent envelopes for the failure points of the composites.



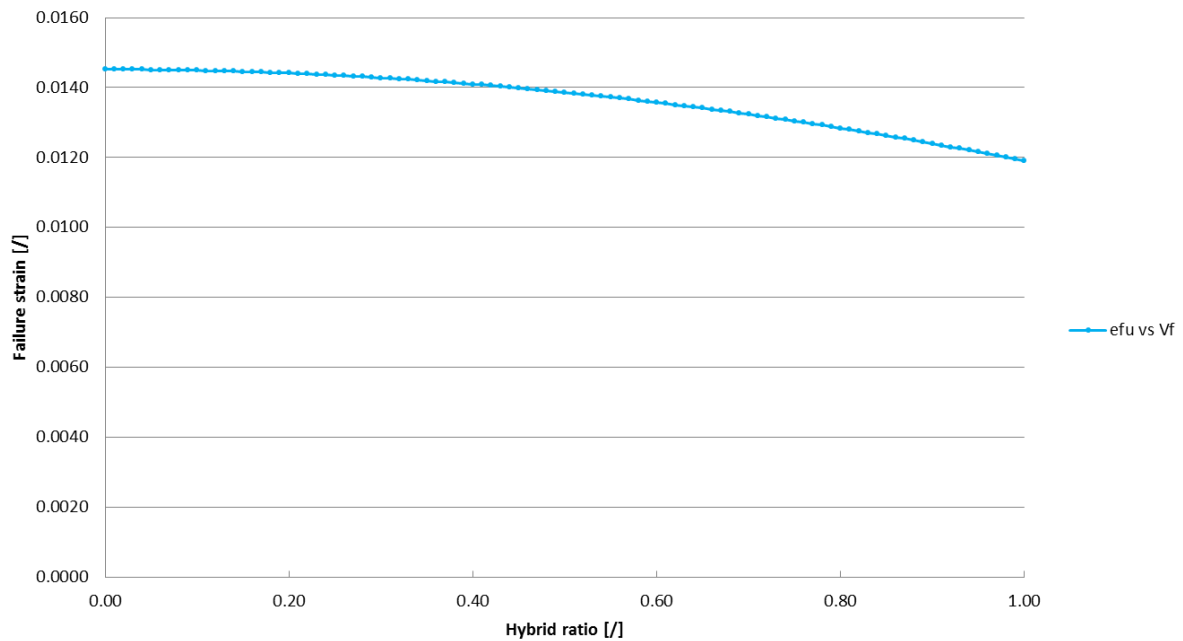


Figure 7. Hybrid effect on “fibre” failure strain  $\epsilon_{fu}$ , with  $H = 1.22$  eq (10)

A good agreement is observed for the hybrid model envelopes (fully drawn red and blue curves), which are clearly over and above the simple model envelopes (red and blue dotted curves). The strength versus “fibre” content diagram in Fig. 5 also shows good agreement with the data points, and with the hybrid model curves clearly over and above the simple model curves. The failure strain versus “fibre” content diagram in Fig. 6 also shows good agreement with the data points, but with the hybrid model deviating rather little from the simple model.

It is suggested that the *hybrid effect* observed in the hybrid carbon – glass fibre composites can be described by the *factor H for the increase of the failure strain* of the low strain (carbon) part of the composite.

## 5 CONCLUSION

The five hybrid composites based on unidirectional fibres of carbon and glass, in an epoxy matrix have been used to investigate the possibility of a hybrid effect. The hybrid effect is observed experimentally by values for both composite strength and composite failure strain, which are increased compared to a simple model, originating from the model of Kelly and Tyson [8]. The introduction of an increase of the failure strain of the carbon fibre part (the “fibre”) of the composite, inspired by the modelling work of Mileiko [10], and described by the factor  $H$  for the increase of the failure strain, results in theoretical curves for strength and failure strain, which are in general agreement with the experimental data. For the present hybrid composites a value of  $H = 1.22$  is required, meaning a positive hybrid effect on “fibre” strain of 22%. It is thus concluded that the simple concept of a hybrid factor  $H$  for the fibre failure strain can describe the observed hybrid effect satisfactorily.

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